INTERACTIONS OF NEGATIVE K MESONS IN FLIGHT IN NUCLEAR EMULSION

Frank Hunter Featherston

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Submitted in partial fulfillment
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IN
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ABSTRACT

A survey of interactions of K^- mesons in flight in nuclear emulsion has been made. Seventy-seven in-flight interactions, seven decays in flight, and four inelastic scatterings were found.

A K^- meson mean free path in nuclear emulsion of 30.0 ± 3.0 cm has been calculated.

A K^--meson lifetime of $1.31^{+.38}_{-.28} \times 10^{-8}$ sec has been calculated.

All interactions were consistent with the conservation of strangeness.

A general qualitative comparison is made between the in-flight and at-rest interactions of K^- mesons.

Two decays in flight were measured, one leading to a definite establishment of a $K^-_{\pi 2}$ decay mode, the other to a strong suggestion of a $K^-_{\mu 2}$ mode.

The angular distribution of the decay pions from 37 Σ hyperons produced by K^- interactions is reported. The distribution tends towards isotropy.

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Out of a welter of early results and symbols, the heavy mesons have come to be known as the K mesons. This assignment of a definite name to these mesons by no means connotes the same unanimity and simplicity of characteristics and properties as are associated with the older well-established particles. In truth, within the realm of K mesons, it has been found necessary to present a more precise listing of these particles, based first, of course, upon electric charge, but more importantly, upon the several ways in which the K meson can decay (more properly, a phenomenological classification).

On this basis the so-called heavy or K mesons, can be listed as follows, with the decay modes indicated [1, 2]:

$K^+_{\pi 3}$, τ^+	$K^+ \rightarrow \pi^+ + \pi^- + \pi^+$
τ'^+	$K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$
$K^+_{\mu 2}$	$K^+ \rightarrow \mu^+ + \nu$
$K^+_{\pi 2}$, θ^+	$K^+ \rightarrow \pi^+ + \pi^0$
$K^+_{\mu 3}$	$K^+ \rightarrow \mu^+ + \pi^0 + \nu$
K^+_{e3}	$K^+ \rightarrow e^+ + ? + ?$
θ^0, θ^0_1 (?)	$K^0 \rightarrow \pi^+ + \pi^-$
	$(K^0 \rightarrow \pi^0 + \pi^0)$
θ^0, θ^0_2 (?)	$K^0 \rightarrow \pi^\pm + e^\mp + \nu$
	$K^0 \rightarrow \pi^\pm + \mu^\mp + \nu$ (?)
$K^-_{\pi 2}$	$K^- \rightarrow \pi^- + \pi^0$
$K^-_{\mu 2}$	$(K^- \rightarrow \mu^- + \nu)$
$K^-_{\mu 3}$	$(K^- \rightarrow \mu^- + \pi^0 + \nu)$
K^-_{e3}	$K^- \rightarrow e^- + (?) + (?)$
$K^-_{\pi 3}$, τ^-	$K^- \rightarrow \pi^- + \pi^- + \pi^+$
	$(K^- \rightarrow \pi^- + \pi^0 + \pi^0)$

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In this listing, the symbol shown on the left of each decay mode is the presently accepted code by which each of the decay modes is designated. The "τ" and "θ" symbols have persisted from the earlier and original designations of these particular decay modes of the K meson. Those decay modes in parentheses have not actually been observed, but are to be expected from charge symmetry.

<u>Strangeness</u>

From this formidable listing of K-meson decay modes, one could quite properly ask whether we are witnessing the decay of two or more different particle species or whether we are seeing the several decay modes of a single species of particle, as the "K" designation implies.

This first question of the multiplicity of decay of the K meson is quickly joined by another experimental puzzle Both hyperons and heavy mesons are abundantly produced in high-energy nuclear interactions, which means copious production on a time scale of the order of 10^{-23} sec; yet the lives of these particles, once they are produced, are very long by comparison ($\sim 10^{-8}$ to $\sim 10^{-10}$ sec). This discrepancy of approximately 10^{13} units of time scale is a seeming contradiction of reversibility principles, by which one would expect the decay of these particles in something akin to 10^{-23} second.

A suitable explanation of these effects began to take form in 1952 when Pais proposed that heavy mesons and hyperons can be produced only in pairs, i. e., in association with each other [3]. This associated production scheme indicated that there are certain selection rules that prevent strong interactions from being operative as part of the decay mechanism.

Finally in 1954, Gell-Mann, Nishijima, and others put forth the hypothesis that explained the apparent dilemma [4]. They

introduced a new property of matter, "strangeness," and stipulated certain selection rules based upon the assignment of a new quantum number to each of the particles in a process (this new number itself they called "strangeness", S). Certain properties of this new number were that it (1) must be integral, (2) could be either positive or negative, and (3) would be a constant of motion in strong interactions, but would change by ± 1 in weak interactions.

From this scheme of things, particle-interaction processes were divided into three classes:

a. <u>Fast Interactions</u> (i.e., direct production)

(1) time scale $\sim 10^{-23}$ sec.

(2) satisfaction of all conservation laws (energy, momentum, angular momentum, parity, charge, heavy particle number, and strangeness). Thus, $\Delta S = 0$.

(3) process does not include emission of a gamma ray.

b. <u>Electromagnetic Interactions</u>

(1) involve the emission of a gamma ray.

(2) weaker by 1/137 than the fast reactions

(3) proceed on a time scale of $\sim 10^{-17}$ sec.

c. <u>Slow Interactions</u>

(1) decays

(2) proceed on a time scale of 10^{-10} sec.

(3) can violate parity considerations

(4) $\Delta S = \pm 1$

Thus, (a) would be the strong interactions which involve baryons, antibaryons, and mesons. We are here in the region of fully nuclear forces, in which mesons and hyperons are produced in high-energy nuclear interactions. The electromagnetic interaction (b) is the natural mechanism whereby the photon involves itself with all charged particles.

The slow (or weak) interactions (c) are the beta-decay process, the various heavy-meson and hyperon decays, and μ-mesonic absorption and decay.

The assignment of strangeness quantum numbers to the various particles is as follows:

$S = 0$:	$p, n;\ \pi^+, \pi^0, \pi^-$
$S = 1$:	K^0, K^+
$S = -1$:	$K^-, \overline{K}^0; \Lambda^0; \Sigma^+, \Sigma^0, \Sigma^-$
$S = -2$:	Ξ^0, Ξ^-

It is well to remember that two charge-conjugate particles must have equal and opposite values of S, because in a fast interaction a particle can be transposed to the other side of the reaction and become its own antiparticle without changing the fast nature of the reaction.

One finds the most direct experimental support of strangeness from a consideration of the charge degeneracy of strange-particle states and the zth component of the isotopic spin. From π-meson physics there comes an expression relating these:

$$Q - I_z - N/2 = 0,$$

where Q is the charge,

I_z is the third component of the isotopic spin,

N is the number of nucleons.

If, through some mechanism in strange-particle interactions, the conservation of isotopic spin remains but the above relation does not hold, i.e.,

$$Q - I_z - N/2 \neq 0,$$

then this sum must still be a quantity that is additively conserved, since Q, I_z, and N are all conserved separately. Thus, the basis of the strangeness scheme is a postulation that a new quantum number,

$$S = 2(Q - I_z - N/2),$$

can correlate and explain the strange-particle interactions.

An illustrative test of this is readily found in the Σ hyperons. The Σ^- has $S = -1$, $Q = -1$, and $N = 1$. I_z thus equals -1. This indicates that there must be two additional particles of mass similar to that of the Σ^-, with $I_z = 0$ and 1, and $Q = 0$ and +1, respectively. Experiment has found two such particles satisfying these conditions, Σ^0 and Σ^+.

The consistency of its explanations has been the remarkable feature of the strangeness concept. There are no known violations of the strangeness-selection rules. Associated production, too, appears to be the order of business. As an explanation, the scheme has done yeomen's service in pointing the way through the dense underbrush of much contemporary research.

Nuclear Emulsions as a Research Tool

The techniques of high-energy particle research are necessarily of a very specialized nature. There are four general experimental systems used in high-energy particle research,

(1) nuclear photographic emulsions,

(2) cloud chambers,

(3) bubble chambers,

(4) scintillating and electronic counting networks.

Each of the four systems has both advantages and limitations peculiar to itself. Employment of a given system in a specific application may enhance or diminish certain of its capabilities.

As a stopping medium, nuclear emulsions are the heaviest by far of the investigative media, having a density of about 3.85 g/cc (average density of Ilford G. 5 emulsion) [5]. The basic elemental constituents of such an emulsion, with the corresponding approximate percentage compositions, by weight, are [5]:

Silver	47.5%	Hydrogen	1.4%
Bromine	35.0	Oxygen	6.5
Iodine	0.3	Nitrogen	1.9
Carbon	7.2	Sulfur	0.2

As a research tool, the emulsion provides a means for direct visual survey and measurement of the tracks left by ionizing particles as they pass through the emulsion stack. (Neutral particles of course, leave no tracks.)

A particle entering an emulsion may

(1) Suffer energy degradation and slowing down, but succeed in leaving the emulsion; or

(2) interact (or annihilate) with one of the constituent elemental nuclei while in flight; or

(3) while in flight in the emulsion, decay, with the resulting particle(s) continuing on in the emulsion; or

(4) be progressively slowed down until it comes to rest in the emulsion. Characteristically, then, the particle can either (if negative) be absorbed into a constituent nucleus, or (if positive) decay.

With a proper selection of physical parameters, an emulsion stack provides a wonderfully compact and portable means for observing the in-flight and terminal behavior of ionizing particles Also, because of its great stopping power, the nuclear emulsion is a useful device for coping with short-lived particles when one is attempting to obtain a

measure of mean lifetime of the order of 10^{-8} to 10^{-13} sec. This is made possible through the greater density of the medium, which causes many of the particles to come to rest before they decay.

As one of the oldest of high-energy particles research systems, the art of employing nuclear emulsions has given rise to many refined auxiliary techniques. Through the use of these techniques one is able to

(1) make an exhaustive analysis of specific and unusual events,

(2) make very accurate mass determinations,

(3) accomplish ready and reliable identification of particles,

(4) precisely predict the response of the system to ionizing particles of any mass (this makes the emulsion well suited for exploratory detection attempts [6]),

(5) make accurate ionization measurements.

The one important factor to appreciate when considering nuclear emulsion results in that the interacting nuclei of the emulsion proper are of several types, covering a wide range of atomic numbers. Silver and bromine nuclei are by far the most numerous and the heaviest, with an average A of 94. Hence, any discussion of emulsion results will be conditioned by this fact. This is not, as might be hastily inferred, a completely deleterious effect; for as pleasant-appearing as the simpler interaction phenomena of the bubble chambers may appear, particle interactions in complex nuclei have a definite appeal of their own.

II. GENERAL EXPERIMENTAL METHOD

Exposure and Development

This comprehensive study of a group of K^- mesons in flight interactions in nuclear emulsion is a modest (but typical) example of the directed application of research effort, made possible by the availability of relatively intense beams of artificially produced K mesons from the Bevatron.

In this instance an emulsion stack of Ilford G. 5 stripped nuclear emulsion, composed of 108 pellicles, each 4 by 7 inches and 600 microns thick, was exposed to a momentum-selected K^- beam of 420 Mev/c. Momentum selection was accomplished by utilizing the magnetic field of the Bevatron itself; quadrupole lenses were used to increase the intensity of the beam. This exposure was the cooperative effort of Gerson and Sulamith Goldhaber and Warren W. Chupp at the Berkeley Bevatron.

The beam to which the stack was exposed contained a mixture of both negative π mesons and the desired K^- mesons (in the approximate ratio of 3000 to 1). The π mesons presented ionization tracks of near-minimum intensity in the emulsion at this particular momentum; hence, they provided a convenient built-in comparative measure of ionization.

The K^- beam was emitted at 0° relative to the target. The beam was lead undeviated through the quadrupole focusing system, which meant that a background of contamination could appear in the exposure because of spurious products produced by portions of the beam striking the yokes of the focusing magnets. To remove this source of contamination, a sweeping magnet was placed behind the quadrupole system to remove all positive particles (i.e., protons).

The emulsion stack was aligned for exposure so that its long dimension was longitudinally placed in the beam. Thus, the particle tracks were parallel to the emulsion layers; the mean range of K^- mesons of this momentum (10.2 cm) was, conveniently, about two-thirds the length of the plate.

Development of the stack followed a modified "Bristol" procedure. Subsequent location of the "x" and "y" coordinates of a given position within each plate-mounted pellicle was facilitated by the contact printing of a grid system of coordinates on the surface of the emulsion, with numbered grids occurring every millimeter [7].

Scanning and Measurement

Inspection of the plate-mounted and developed layers of a photographic nuclear emulsion is accomplished with high-resolution microscopes. This "scanning" can be executed by following either of two general techniques: (1) area scanning, in which the observer looks at all events within a given area of the plate, looking for interaction stars, and subsequently following the causative particle back from the event to where it entered the emulsion; (2) along-the-track scanning, in which scanning is done transversely across the beam of entering particle tracks near the edge of the plate. On the readily determined basis of their relative degree of ionization, tracks of the appropriate ionization can be followed and their terminal behavior recorded.

Along-the-track scanning introduces a minimum of bias towards finding or rejecting any particular species of terminal behavior. All types of track endings are seen with equal facility, since all tracks are followed from where they enter the emulsion, before an event occurs. Area scanning, on the other hand, must--by the nature of the technique and from the inevitable human considerations involved--result in not seeing all the events with no secondaries or with light,

minimal secondaries. Area scanning has its place under certain circumstances (cosmic-ray exposures, or surveys for particular types of interactions or interaction products, for example).

In the exposure study made in gathering the data for this report, transverse scanning near the exposed edge of the plates readily revealed those particles with a degree of ionization approximately 1.8 times minimum, the theoretically predictable degree of ionization characteristic of K^- mesons of the selected momentum in Ilford G. 5 emulsion.

Each track so selected was followed to its end in the emulsion. Every reported event was unambiguously identified as being caused by a K^- meson, either by successive grain counts (ionization measurements) if sufficient track length was available, or by multiple-scattering techniques, utilizing the constant-sagitta method, to obtain a measure of the particle's $p\beta$, to be compared with its relative ionization.

All interaction products were followed either to their endings or until they left the stack. All prongs not identifiable as electrons, mesons, hyperons, or hyperfragments were termed "stable charged" prongs and were assigned kinetic energies from their measured ranges upon the assumption of a protonic mass. This leads to a resulting underestimate of the kinetic energy of approximately one third of the particles, which are actually deuterons, tritons, alpha particles, or recoil fragments. All prongs less than 5 microns long were termed "recoils" and were not considered in either prong or energy distributions.

III. RESULTS

Summary

All together, seventy-seven interactions in flight of K^- mesons have been identified. Seven additional events were identified as decays in flight of K^- mesons; four other events have been established as representing the inelastic scattering of K^- mesons by the constituent nuclei of the emulsion.

Of the 77 in-flight events, 13 produced charged Σ hyperons, 10 of which had visible associated π mesons. Three events produced charged Σ hyperons without any visible π mesons. Similarly, 12 events produced π mesons without identifiable Σ hyperons. Thus, 17% of the event produced identifiable Σ hyperons; 29% of the events produced π mesons; 13% of the events produced visible Σ hyperons and π mesons in association.

Of the 13 Σ's seen, two were Σ^-, five were Σ^+, and six decayed in flight and hence could be either Σ^+ or Σ^-. Of these six, one could be considered Σ^- because the Σ itself was the sole visible reaction product; thus, there is a possibility that the interaction went via the available channel:

$$K^- + n \longrightarrow \Sigma^- + \pi^0.$$

One star produced a hyperfragment, which decayed nonmesically.

One of the ten observed $\Sigma + \pi$ events was established as representing the capture of a K^- meson in hydrogen [8].

Forty-eight of the events produced only charged stable, i.e., "evaporation", prongs.

Three of the K^- tracks ended in flight with no visible prongs. These are classified as disappearances and are included in the total of 77.

These results represent a scanning effort of 25.71 meters of K^- meson track (in which, in addition, 226 K^--meson absorptions at rest have been identified) [9]. This figure for track length includes two corrective factors: (1) The last 2 mm of each track that comes to rest (corresponding to the last 16 Mev of kinetic energy) have been omitted from consideration because a decay in flight in this region is difficult to identify; (2) The first 5 mm of each track have not been included because the primary particle causing an event in this early region cannot be easily identified as a K particle. Table I is a tabulation of the length of track scanned in the indicated energy intervals.

TABLE I

Length of K^- Meson Track Scanned in Energy Intervals

Energy Interval (Mev)		Track Length (cm)
16 - 30		94.4
30 - 40		90.5
40 - 50		116.9
50 - 60		132.8
60 - 70		156.1
70 - 80		167.3
80 - 90		193.2
90 - 100		221.6
100 - 110		221.7
110 - 120		237.1
120 - 130		261.2
130 - 140		268.7
140 - 150		272.6
150 - 160		124.8
160 - 170		12.1
	Total	25.71 meters

Mean Free Path of K^- Mesons in Nuclear Emulsion

When the track length and number of events of this report are combined with the corresponding data from Iloff [2], who reports 21 in-flight interactions in 4.90 meters of track, the mean free path in nuclear emulsion for K^- mesons is found to be

$$\lambda = 30.0 \pm 3.0 \text{ cm.}$$

This corresponds to a nuclear radius $R = (1.32 \pm 0.07 \times 10^{-13})$ $A^{1/3}$ cm.

Mean Lifetime of the K^- Meson

The mean lifetime of the K^- meson, τ_{K^-}, equals T/N, where T is the algebraic sum of the proper slowing-down times for each K^- track, calculated from where the particle is first registered to where it decays or interacts in flight, or up to a point 2 mm before it comes to rest. N is the total number of observed decays. T is calculated on the basis of the tables of Barkas and Young [10].

The results of this investigation show seven (7) decays in flight with a corresponding proper slowing-down time of 13.85×10^{-8} sec. Again, combining these results with those of Iloff et al. [11], who report 13 decays with a corresponding total proper slowing-down time of 12.4×10^{-8} sec, one obtains

$$\tau_{K^-} = 1.31^{+.38}_{-.28} \times 10^{-8} \text{ sec.}$$

(The error quoted is based on confidence limits for 68% probability for 20 events).

This mean life, of course, is a mixture of the several possible K^- decay modes. It is to be compared with

$$\tau_{K^-} = 1.49^{+.22}_{-.24} \times 10^{-8} \text{ sec,}$$

recently reported from the results of a counter experiment [12]. This counter-determined value is based on an experiment conducted four mean lives from the target; the value presented in this report is based on an investigation two mean lives from the target.

Interaction Considerations

The conservations of strangeness, charge, and heavy-particle number allow only the following one-nucleon interactions of K^- mesons at rest:

(1) $K^- + p \rightarrow \Sigma^+ + \pi^-$,

(2) $\rightarrow \Sigma^- + \pi^+$,

(3) $\rightarrow \Sigma^0 + \pi^0$,

(4) $\rightarrow \Lambda^0 + \pi^0$,

(5) $K^- + n \rightarrow \Sigma^- + \pi^0$,

(6) $\rightarrow \Sigma^0 + \pi^-$,

(7) $\rightarrow \Lambda^0 + \pi^-$.

Certain types of two-pion reactions are allowed, but are negligible from phase-space considerations. Multiple nucleon capture also is allowed, but is considered to make only a small contribution ($\sim$10%) [9].

These interactions come about through the capture at rest of the K^- meson in a Bohr orbit of the atom, with subsequent absorption into the nucleus. These absorptions are strong ("fast") interactions, occurring in $\sim 10^{-23}$ sec. They must, of necessity, proceed with positive Q values.

For the $K^- + p$ reaction, (1) through (4), one must have clearly in mind the difference between capture of a K^- meson by a proton that is bound in the nucleus, and K^- capture by a free proton. The bound proton is moving in a nuclear potential distribution; consequently, when it captures a K^- meson, the reaction products must find their way free of the nucleus. Thus, their visible energies are modified by

their escapes. The parent nucleus is also left in an excited state and will emit so-called "evaporation" prongs.

By contrast, K^- capture by a free proton displays none of these complications. The full Q of the reaction is carried away in the primary reaction products. Kinematic resolution of these events is thus possible through accurate measurement of the secondary tracks.

<u>Comparison with K^+ Mesons</u>

In addition to the K^--absorption interactions listed in (1) through (7), the K^- meson is permitted to interact with matter while in flight by two additional mechanisms.

a. Scattering, as permitted by

$$K^- + p \rightarrow K^- + p$$

or $$K^- + n \rightarrow K^- + n.$$

This scattering corresponds to inelastic scattering from a nucleus, but in scattering from hydrogen, elastic scattering is also possible.

b. Charge exchange, wherein

$$K^- + p \rightarrow \overline{K}^0 + n.$$

It is in these types of interaction, i. e., scattering and charge exchange, that positive K mesons display an exact correspondence to negative K-meson interaction types. Thus, the following K^+ meson interactions in flight are permitted:

a. Scattering:

$$K^+ + p \rightarrow K^+ + p,$$
$$K^+ + n \rightarrow K^+ + n;$$

b. Charge Exchange:

$$K^+ + n \rightarrow K^0 + p.$$

Because K^+ mesons have a strangeness value of +1, they are forbidden from undergoing absorption interactions corresponding to

the types (1) through (7) listed for K^- mesons. Thus, a K^+ meson that comes to rest in matter suffers Coulomb exclusion from the surrounding nuclei and can only decay (via any one of several decay modes).

Interactions in Flight versus Absorptions at Rest

In the published literature only a limited attempt has been made to compare K^- in flight behavior and K^- absorptions at rest [13]. This condition has been dictated by statistics, because in the energy region explored, the preponderance of K^- events in emulsion have been the absorptions of K^- mesons that have come to rest.

Although this report significantly increases the published statistics for in-flight interactions, the significance is still such as to permit only limited qualitative comparison. No doubt the immediate future will see the issuance of many data now in the incubation stage. Then, quantitative comparisons can be made.

Prong Distribution

Figure 1 is a comparison of the prong distributions produced by K^- absorptions at rest and K^- interactions in flight. The "at rest" portion is the published compilation of the 1956 Rochester Conference (449 events) [13]. The "in flight" portion represents an improvement of the Rochester data (where 56 events were reported from five separate research groups) by the addition of the 77 events of this report.

Two points can be made from this comparison:

(1) The increase in $\overline{N}$, the average number of prongs per star, for stars in flight reflects an increase in nuclear excitation in these events.

(2) There is justification for the premise that charge exchange is not a very large part of the K^- absorption cross section because there is no increase (in fact, there is a percentage decrease) in the number of stars with zero or one prong.

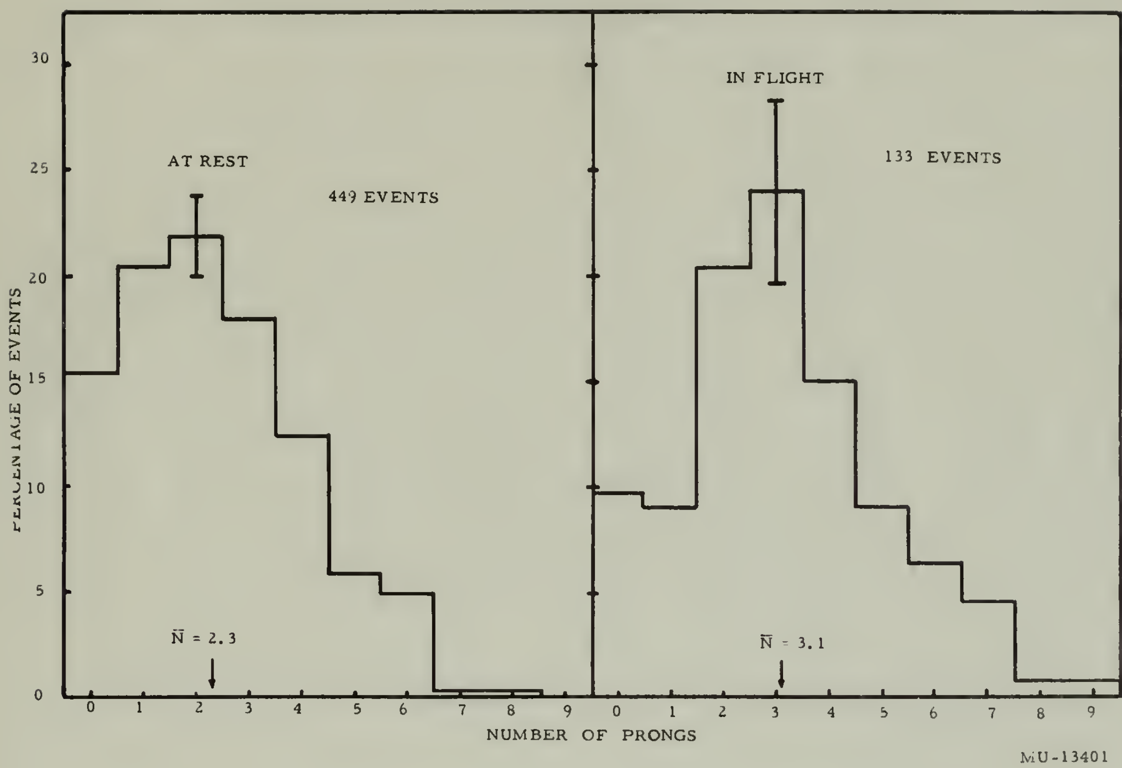

Fig. 1. Prong distributions for K^--meson events at rest and in flight.

Effects of K^--Meson Kinetic Energy

The average kinetic energy at interaction of the 77 K^- mesons of this report was 105 Mev. Because one is looking for comparative effects between K^- interactions in flight and K^- absorptions at rest, an obvious effect is to see how (or whether) this 105 Mev asserts itself. The increase in $\overline{N}$ in the previous prong distribution is doubtless one effect. Again, one must bear in mind the limited in-flight statistics.

Thirteen of the in-flight events produced single charged hyperons, and ten of these events exhibited an associated π meson. Only one of these ten constituted an interaction with a free proton; the other nine events occur with bound protons.

Figure 2 shows a comparison of the total kinetic energy of $\Sigma + \pi$ combinations for in-flight interactions and at-rest absorptions. The approximate mean energies of each distribution are, respectively, 140 and 80 Mev. The Q available from the general reaction $K^- + \text{nucleon} \rightarrow \Sigma + \pi$ is about 104 Mev. The "at rest" distribution forms a peak at about 80 Mev, which means that the Σ and π succeed in escaping the reaction volume with about 80 Mev of their original 104 Mev. The difference in energy goes into nuclear excitation, and possible inelastic scattering losses of the particles while still in the dense nuclear region.

The "in flight" portion of Fig. 2, then, would indicate that the primary reaction products carry off an additional 60 Mev of the now-available 105 Mev of kinetic energy, the remainder of this kinetic energy going into increased nuclear excitation (as indicated in the prong distribution, Fig. 1). The use of these specific energy figures is meant to convey the degree or apparent order of the effect seen, rather than to mean anything truly quantitative.

Analysis of K⁻ Meson Kinetic Energy

The average kinetic energy at production of the 17 K⁻ mesons in this experiment was 100 MeV. Because one is looking for interactions [illegible] between K⁻ interactions in flight and K⁻ [illegible] at rest, [illegible] for [illegible] that [illegible]. The [illegible] in the previous prong distribution is [illegible] [illegible] reason, one must bear in mind the [illegible] in-flight [illegible].

[illegible] of the in-flight events produced single charged hyperons, and one of these events exhibited an associated π meson. Only one of these [illegible] an interaction with a free proton; the others were [illegible] with bound protons.

Figure 1 shows a comparison of the total visible energy of Σ + π combinations for in-flight interactions and at-rest interactions. The approximate mean energies of each distribution are, respectively, [illegible] and [illegible] MeV. The Q available from the general reaction K⁻ + nucleon → Σ + π is about [illegible] MeV. [illegible] forms a peak at about [illegible] MeV, which [illegible] that the Σ and π [illegible] in escaping the reaction volume with about [illegible] MeV of their original [illegible] MeV. The difference is [illegible] [illegible] into nuclear excitation and possible inelastic scattering losses of the particles while still in the same nuclear region.

The "in flight" portion of Fig. 1 shows [illegible] indicate that the primary reaction products carry off no additional [illegible] MeV, of the non-available [illegible] MeV of kinetic energy. The [illegible] is that [illegible] energy going into excitation of the nucleus [illegible] reflected in the prong distribution (Fig. 1). The [illegible] [illegible] is [illegible] to [illegible] the degree of [illegible] [illegible] on the [illegible] [illegible] [illegible] [illegible] [illegible] interactions.

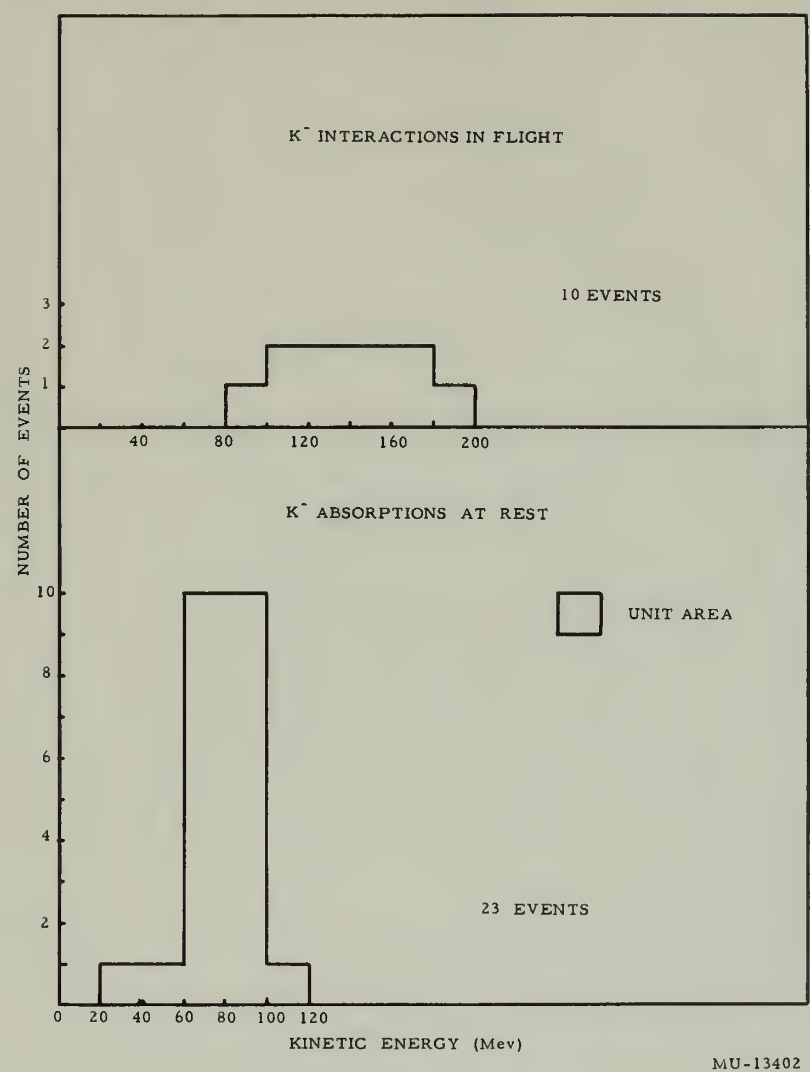

Fig. 2. Comparison of sums of kinetic energies of associated Σ and π.

Total Visible Energy Spectrum

Figure 3 is another comparative distribution, this time showing the total visible energy spectra. The following constitute the criteria for energy-value assignments:

(1) All charged stable prongs were assigned kinetic energies on the basis of an assumed protonic mass from their measured ranges. In each case, then, 8 Mev of binding energy was added (a minimum amount of energy necessary to remove a proton from the nucleus). As previously pointed out, this procedure actually sets a lower limit to approximately one third of this portion of the spectra.

(2) Pi mesons were assigned their measured kinetic energies plus a rest mass energy of 139.5 Mev.

(3) Hyperons were assigned their measured kinetic energies plus a Q value taken as the difference between the hyperon mass and the proton mass, i.e., 1189 Mev minus 938 Mev, which equals 251 Mev.

Bearing in mind, again, the difference in number of events at rest and in flight, one notices the following:

(a) The percentage decrease in the number of stars with less than 20 Mev. This is to be expected since it would take only a portion of the available 105 Mev of K^- meson kinetic energy going into increased nuclear excitation, to bring about this low energy shift.

(b) The identified $\Sigma + \pi$ events (cross-hatched) assert themselves at the extreme right of each distribution. The "in flight" events shift almost as a block, as previously indicated in Fig. 2.

One would expect some fraction, say about half, of the 105 Mev of average K^- kinetic energy to appear as a general translational effect along the entire length of the "in flight" distribution. Qualitatively, such an effect is observed.

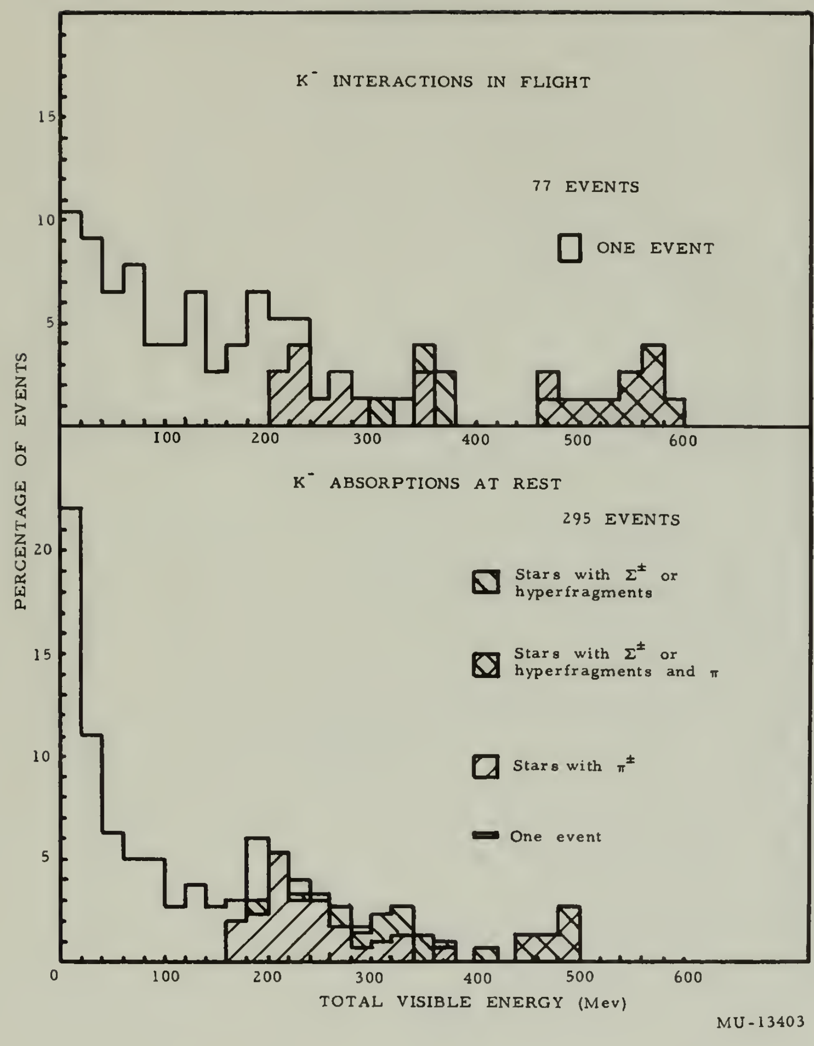

Fig. 3. Comparison of total visible energy release.

The Pi-Meson Spectrum

Of considerable interest in the general study of K mesons is a determination of the frequency with which K^- mesons interact in the several available channels. A first approach would be to determine the $\Sigma^{\pm 0}/\Lambda^0$ production ratio. Because the Λ^0 hyperon will not register in the investigative medium, one must try to deduce this ratio from associated conditions that can be observed. This means that the observed charged-pion spectrum can be quite meaningful.

The statistics of the π-meson spectrum from K^- absorptions at rest are now quite good. Figure 4 shows a histogram of 169 such pions [9].

The π mesons produced in the free-nucleon capture of a K^- meson have characteristic kinetic energies of 90 or 150 Mev, depending upon whether the associated hyperon is a Σ or Λ. Figure 4 clearly displays a peak at 60 Mev both for the over-all distribution and for those pions produced in associated with charged hyperons. This coincidence of peaks makes a very strong argument for the preferred production of energy-degraded 90-Mev π mesons produced in the $\Sigma + \pi$ reaction (as opposed to the $\Lambda + \pi$ type of reaction).

Figure 5 is a constant-area histogram showing the kinetic-energy distribution of the 22 charged pions observed from the 77 in-flight interactions of this report. The pion energies were determined by ranges where possible, or by grain count if the particle left the emulsion stack.

This spectrum of pions from the in-flight interactions is based on relatively poor statistics, but it does have one feature that subtly enhances the contention that Σ production is significantly preferred to Λ production; specifically, the pronounced high-energy peaking shows that higher-energy π mesons are not excluded from making their presence felt, _if_ they _are_ produced in the first place. This tends to

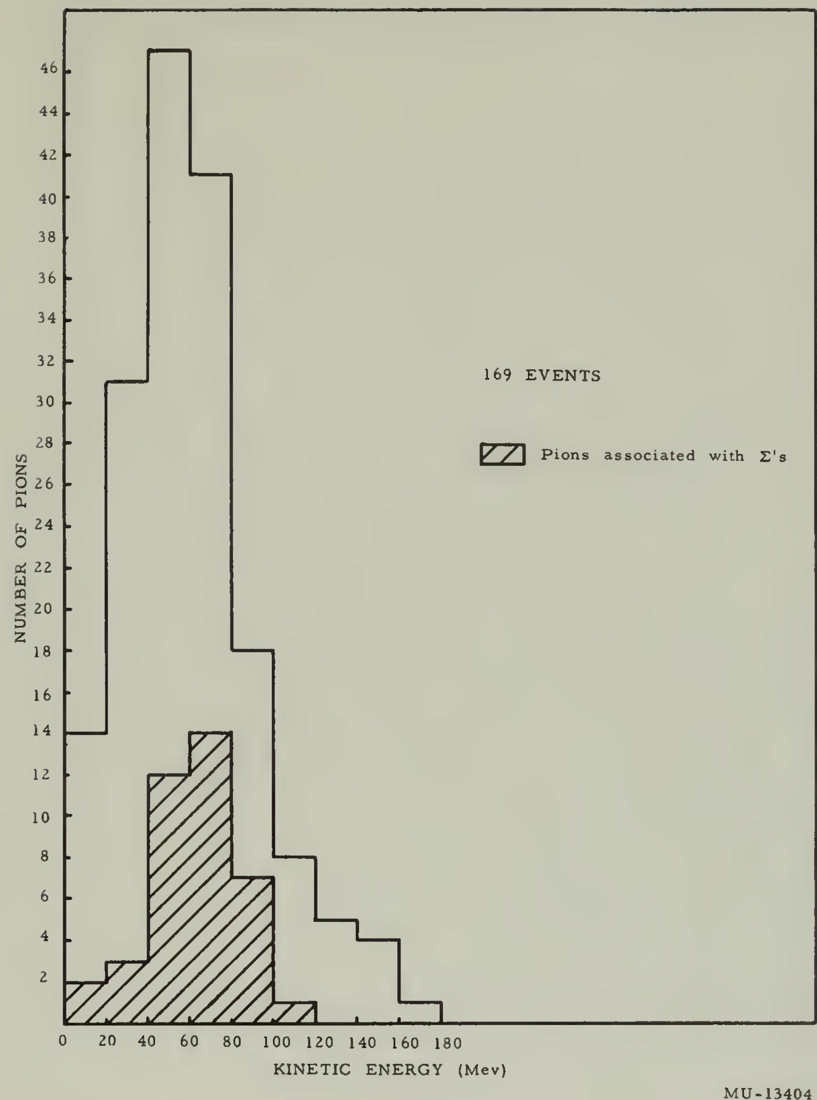

Fig. 4. Pi-meson spectrum from K^- absorption stars[9].

Fig. 5. Kinetic-energy spectrum of π mesons from K^- interactions in flight. (Illustration is a constant-area histogram, reflecting the error in energy determination.)

negate arguments that have said that there is a very strong bias against the emission of high-energy pions from complex-nuclei interactions (arguments based on the peculiarities of pion scattering inside the nucleus).

The inference, again, is that the 150-Mev pions of the $\Lambda + \pi$ reactions are infrequently produced. Thus the $\Lambda + \pi$ interaction channels for K^- mesons appear to be small.

Decays in Flight

In this study of K^- in-flight interactions, seven events were in-flight decays. An in-flight event was classified as a decay if it exhibited only one secondary prong, this prong having a degree of ionization less than that of the primary at the point of the decay. Such an event could represent an in-flight interaction with a single π-meson secondary. However, a survey of K^- absorptions at rest shows this to be a very infrequent star type (8 out of 325, in one survey) [2]. Since in-flight interactions have a much greater tendency to display evaporation prongs because of increased nuclear excitation, the frequency of occurrence of single π events is even further reduced.

Of the seven decays observed, two displayed secondaries that were amenable to measurement. One secondary was emitted at a space angle of 57.8^{o} relative to the parent K^- meson. As Fig. 6 shows, this event (A) unambiguously resolves itself as representing the decay of a K^- meson via $K^-_{\pi 2} \rightarrow \pi^- + \pi^0$.

The second decay (B) occurred at a space angle of 57.5^{o} relative to the K^- meson. Its kinematic resolution is not so well defined as is that of event A. Both events are displayed on Fig. 6, since they occur at nearly the same space angle. The angular error is very small ($\sim$ 1%), and this region of comparative momenta is fairly insensitive to small changes in space angle.

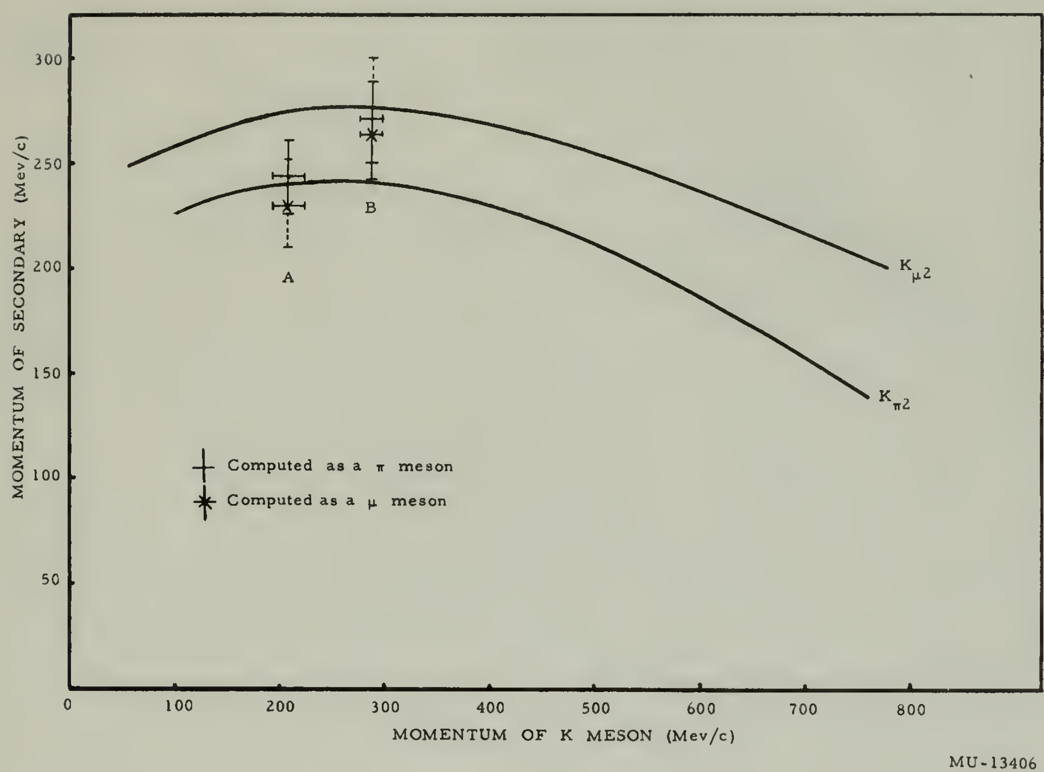

Fig. 6. K^--meson decays: momentum of the secondary particle as a function of K^--meson momentum (for a laboratory angle of 58.0°).

Event B is more nearly commensurate with a $K^-_{\mu 2} \rightarrow \mu^- + \nu$ decay mode, as Fig. 6 indicates. When its resolution is attempted by use of a particle of π-mesonic mass, the fit to the necessary curve ($K^-_{\pi 2}$) is worse, further strengthening the $K^-_{\mu 2}$ conclusion.

K^- Meson Inelastic Scattering

Four inelastic scatterings of K^- mesons were observed. Table II summarizes the results.

TABLE II

Results from inelastic scattering of K^- mesons

Kinetic energy of K^- meson at scatter (Mev)	Fractional energy loss, $\Delta E/E$	Space angle of scatter (degrees)
38	0.58	55.9
58	0.62	81.8
103	0.48	58.8
138	0.55	102.8

From isotopic spin considerations, the K^- ratio of (charge exchange/inelastic scattering) is $\lesssim$ 2. Thus, the limit on the charge-exchange contribution to the absorption cross section is $\lesssim$ 8% [9].

The large fractional energy loss ($\Delta E/E$) indicates that an attractive (negative) potential may be operating in K^- scattering. In addition to the four inelastic scatterings reported here, a recent summary of emulsion data [14] indicates seven other events, all with $\Delta E/E$ greater than 0.40. This effect is the opposite of that observed in the scattering of K^+ mesons. There the energy loss in inelastic collisions is small, $\Delta E/E \approx 0.35$, which can be ascribed to a repulsive potential [15].

K^- + H Compilation

For comparative purposes, a compilation of published results of K^- + H scattering and absorption is given below.

Group	Energy Interval (Mev)	Absorptions in flight	Number of scatters	Path length (meters)
Goldhaber et al. [9]	16 - 160	1	1	33
White et al. [16]	16 - 150	1	10	30
Barkas et al. [17]	30 - 90	2	6	49.5
		4	17	112.5

From this the following K^- + H cross sections have been calculated:

(1) Scattering 47^{+14}_{-11} mb.

(2) Absorption 11^{+9}_{-5} mb.

(3) Total 58^{+16}_{-13} mb.

K^- Interactions in Flight: Conclusions

Within the statistics of the data of this report, there is no apparent major difference between "in flight" interactions and "at rest" interactions of K^- mesons in nuclear emulsion. Interactions in flight display greater nuclear excitation, attributable to the extra available kinetic energy. The inelastic scattering data indicate the presence of an attractive nuclear potential.

Σ Decay Spectrum

The charged Σ hyperons can decay via

$$\Sigma^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

or $$\Sigma^- \rightarrow n + \pi^- \quad .$$

The angular distribution of these decay products with respect to the hyperon's in-flight direction can be used to investigate:

(1) Parity considerations. Lee and Yang [18] have shown that if the Σ has mixed parity, the decay spectrum should show a forward-backward asymmetry.

(2) Spin of the Σ hyperon. After the folding of such an angular distribution about 90°, one can get an indication of spin, independent of parity doublet considerations. Thus, an isotropic folded distribution would indicate a spin of 1/2; any asymmetry would indicate a spin $>1/2$ [19].

A survey has been made of the decays of Σ's produced by K^{-} absorptions at rest and K^{-} interactions in flight. Thirty-seven Σ hyperons with decays have been observed. Of these, 26 were produced by K^{-} absorptions at rest, 11 were produced by in-flight interactions. The angular distribution of the space angle in the center of mass between the initial Σ-hyperon direction and the decay-pion direction was measured.

Figure 7 illustrates the resulting distribution, based on intervals of the cosine of the pion space angle of 1/3, from -1 to +1. This corresponds to equal intervals of solid angle.

The distribution tends towards isotropy.

Σ^{+} Branching Ratio

Of the 37 hyperons observed, 28 decayed at rest, thus giving a definite indication that they were Σ^{+} (Σ^{-} interacts strongly when at rest . A Σ hyperon decaying in flight into a pion can be either Σ^{+} or Σ^{-}). Of the 28 decays at rest, nine decayed via the $(p + \pi^{0})$ mode, the other 19 via the $(n + \pi^{+})$ mode. Detection of the $(n + \pi^{+})$ mode in emulsion work is efficient only to about 90%. Also, only decays at rest can be reliably identified.

Fig. 7. Angular spectrum of decay pions from hyperons produced in K^--absorption stars. (θ is space angle between projected direction of Σ and direction of decay pion (π^+ or π^0, as case may be) in center-of-mass system).

The published results of both emulsion and bubble chamber groups are summarized thus:

Group	$(p + \pi^0)$ mode	$(n + \pi^+)$ mode
Goldhaber et al. [9]	9	19
White et al. [16]	4	8
Barkas et al. [17]	13	13
Fry et al. [20]	26	20
	52	60
Corrected for efficiency	52	~66
Alvarez et al.	27	31
	79	97

Over-all ratio: $\Sigma_p/\Sigma_{\pi^+} = 79/97 = 0.81 \pm 0.12$

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